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NLR-TP-2005-336

Acoustic Array Measurements on a Full Scale Wind Turbine

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This report has been based on a paper presented at 11th AIAA/CEAS Aeroacoustics Conference, at Monterey, California on 23-25 May 2005.
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Customer:	EU/NOVEM
Working Plan number:	AV.1.H
Owner:	National Aerospace Laboratory NLR
Division:	Aerospace Vehicles
Distribution:	Unlimited
Classification title:	Unclassified
	June 2005

Approved by:

Author	Reviewer	Managing department
SO 30/6/05	30/06/05	30/6

Summary

Acoustic array measurements were performed on a three-bladed GAMESA G58 wind turbine with a rotor diameter of 58 m and a tower height of 53.5 m. The goal was to characterize the noise sources on this turbine, and to verify whether aerodynamic noise from the blades is dominant. In order to assess the effect of blade roughness, one blade was cleaned, one blade was tripped, and one blade was left untreated. The acoustic array consisted of 152 microphones mounted on a horizontal wooden platform (15 by 18 m^2), which was positioned about 58 m upwind from the rotor. In parallel to the acoustic measurements, a number of turbine parameters were monitored, such as wind speed, power, turbine orientation, RPM, and blade pitch angle. In total more than 100 measurements were taken at wind speeds between 6 and 10 m/s. Two array processing methods were used to characterise the noise from the turbine. First, the noise sources in the rotor plane were localised using conventional beamforming. These results clearly show that, besides a minor source at the rotor hub, practically all noise (radiated to the ground) is produced during the downward movement of the blades. The noise is produced by the outer part of the blades (but not by the very tip), and blade noise levels scale with the 5^{th} power of the local flow speed. The second processing method employed rotating scan planes to localise the noise sources on the individual blades. It turns out that the tripped blade is significantly noisier than the clean and untreated blades, which is a strong indication of trailing edge noise (rather than inflow turbulence noise). The similar noise levels for the clean and untreated blades suggest that the untreated blade was aerodynamically clean.

Contents

(17 pages in total)

1 Introduction

WIND turbine noise is one of the major hindrances for the widespread use of wind energy. For modern large turbines, the dominant noise source is considered to be aerodynamic noise from the blades. Therefore, the subject of the European SIROCCO project ('Silent Rotors by Acoustic Optimisation') is the design, testing, and full-scale validation of quiet wind turbine blades. The objective is to obtain a noise reduction of 3-6 dB with respect to the current state-of-the-art, without a reduction in power performance. As a first step in the project, acoustic array measurements were performed on an existing baseline wind turbine. The goal was to characterize the noise sources on this turbine, and to verify whether indeed aerodynamic (in particular trailing edge) noise from the blades is dominant. The SIROCCO project can be regarded as the continuation of the previous DATA project, where quiet wind turbine blades were tested on a model scale rotor in a wind tunnel [1].

The measurements were carried out in December 2003, on a three bladed GAMESA G58 wind turbine (rotor diameter 58 m) which was located on a wind farm in northern Spain. In order to assess the effect of blade roughness due to e.g. dirt or insects, prior to the acoustic tests one blade was cleaned, one blade was tripped, and one blade was left untreated. The acoustic array consisted of 152 microphones mounted on a horizontal wooden platform (15x18 m^2), which was positioned about one rotor diameter upwind from the rotor. In parallel to the acoustic measurements, a number of turbine parameters were monitored, such as wind speed, power, turbine orientation, RPM, and blade pitch angle. In total more than 100 acoustic measurements were taken at wind speeds between 6 and 10 m/s (at the standard a height of 10 m). The 35 measurements with the most stable conditions were selected for further processing. Two different acoustic processing methods were applied to characterise the noise from the turbine. With the first method the noise sources in the rotor plane were localised, thus showing the integrated effect of the three blades. The second method was used to localise and quantify the noise sources on the individual blades.

The organisation of this paper is as follows. The experimental method is described in detail in Section 2. The experimental results for both processing methods are discussed in Section 3. The conclusions are summarised in Section 4.

2 Experimental Method

2.1 Test Set-up

The measurements were carried out on a pitch-controlled, three-bladed GAMESA G58 wind turbine, which has a rotor diameter of 58 m and a tower height of 53.5 m (Fig. 1). The turbine was located on the wind farm 'Los Monteros' in Pedrola (northern Spain). In order to obtain a 'clean' inflow, a turbine on the upwind edge of the farm was chosen. About one week before the acoustic tests, one blade was cleaned, the second blade was first cleaned and then tripped, and the third blade was left untreated. Tripping was done using zigzag tape of 0.4 mm thickness over the complete span, at 5% chord on the suction and pressure sides of the blade. In addition to the trip, a sticker was attached to the tripped blade, in order to enable visual identification of the blades.

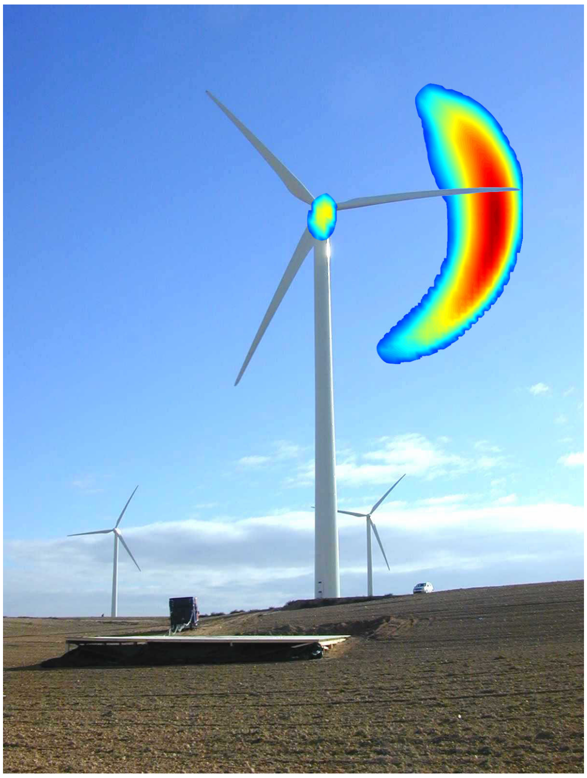

Fig. 1 Test set-up with G58 turbine and microphone array platform. The noise sources in the rotor plane (averaged over several rotations) are projected on

The acoustic array consisted of 152 Panasonic WM-61 microphones, mounted on a horizontal wooden platform of 15x18 m^2, which was positioned about 58 m upwind from the turbine (Fig. 2). As a reference, two calibrated B&K microphones were mounted on the platform as well. All microphones were mounted flush to the surface of the platform, with the membrane parallel to the platform, and without wind screens.

The microphone array had an elliptic shape to obtain approximately the same array resolution in the horizontal and vertical direction, despite the 'view angle' of about 45° (Fig. 2). The ellips was 'pointed' to the right-hand side of the rotor plane, to obtain maximum resolution on the side where the blades move downward and where maximum noise radiation was expected. The array had a high microphone density in the center to ensure good array performance at high frequencies, and a low-density outer part to obtain a good resolution at low frequencies.

2.2 Data Acquisition

Acoustic data from the array microphones were synchronously measured at a sample frequency of 51.2 kHz and a measurement time of 30 s. The acoustic data were processed using a block size of 2048 with a Hanning window and an overlap of 50%, yielding 1500 averages and a narrowband frequency resolution of about 25 Hz. A 500 Hz high-pass filter was used to suppress high-amplitude pressure fluctuations at low frequencies, and thus extend the dynamic range to low pressure amplitudes at high frequencies. The sound levels in this paper are corrected for the filter response. Before the measurements, the sensitivity at 1 kHz was determined for all array microphones using a calibrated pistonphone. The frequency response of the Panasonic microphones was taken from previous calibration measurements. No corrections were applied for microphone directivity, since calibration measurements showed that these effects amounted to less than 2 dB up to 20 kHz, for angles smaller than 75° with respect to the microphone axis. Moreover, this effect is the same for all measurements. Phase matching of the microphones was checked before the measurements using a calibration source at known positions.

In parallel to the acoustic measurements, the following turbine parameters were acquired (sample rate 3 Hz): wind speed, power production, turbine orientation, RPM, blade pitch angle, and temperature. The turbine data were synchronised with the acoustic measurements. The measured wind speed (at the hub) was normalised to the wind speed at 10 m height using the standard wind profile from reference 2. For the present tests this means that the wind speed at 10 m height was taken to be the measured wind speed at hub height multiplied by 0.760.

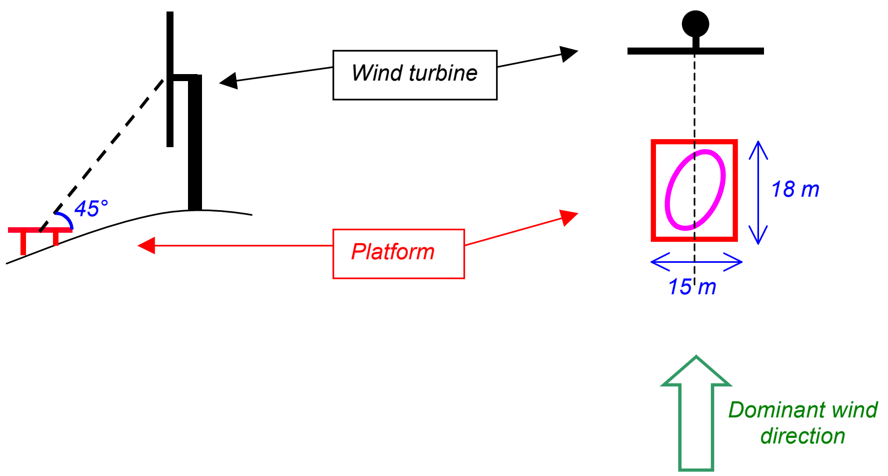

Fig. 2 Side view (left) and top view (right) of test set-up. The microphones were mounted on the platform in an elliptic shape

2.3 Phased Array Processing

The array data were processed using two different methods. With the first method, noise sources in the rotor plane were localised using conventional beamforming [3]. Thus, noise from the rotor hub can be separated from blade noise, and it can be seen where in the rotor plane the blade noise is produced (see e.g. Fig. 1). This method shows the integrated effect of the three blades, averaged over the complete measurement time of 30 s (i.e. several rotations). The first step of this processing involves the calculation of an averaged cross-power matrix which contains the cross-powers of all microphone pairs in the array. To improve the resolution and suppress background noise (e.g. wind-induced pressure fluctuations on the microphones), the main diagonal of the cross-power matrix (i.e. the autopowers) was discarded. A frequency-dependent spatial window was applied to the microphone signals, in order to improve the resolution and suppress coherence loss effects (due to propagation of the sound through the atmospheric boundary layer). The scan plane, with a resolution of 1 m in both directions, was placed in the rotor plane of the wind turbine, and was rotated in accordance with the orientation of the turbine (depending on wind direction). The 6° angle between the rotor axis and the horizontal plane was also accounted for. The effect of sound convection in the atmospheric boundary layer was taken into account by assuming a constant wind speed between the scan location and the microphones. This constant wind speed was calculated as the average wind speed between the rotor hub and the array center, using the standard wind profile in reference 2. Thus, for the present test the average wind speed was taken to be the measured wind speed at hub height multiplied by 0.866. The narrowband acoustic source plots were summed to 1/3-octave bands, and the scan levels were normalized to a distance of 0.282 m [$(4\pi)^{-1/2}$], so that for a monopole source the peak level in the source plot corresponds to the Sound Power Level. The noise sources in the rotor plane were quantified using a power integration method [4]. By defining an integration contour around the whole rotor plane and one only around the hub, noise levels from the hub and the blades were determined.

The second processing method employed three rotating scan planes to localise the (de-dopplerised) noise sources on the three individual blades [5]. This enabled a comparison of the noise from the clean, tripped, and untreated blade. The start position of the scan planes was determined using a 1P tacho signal from the turbine, that was recorded synchronously with the acoustic data. The scan resolution was 0.5 m in both directions, and the scan plane was placed in the rotor plane. Similar to the first processing method, the narrowband acoustic source plots were summed to 1/3-octave bands, and the scan levels were normalized to a distance of 0.282 m [$(4\pi)^{-1/2}$]. Since the source plots of the complete rotor plane indicated that practically all measured noise was produced during the downward movement of the blades (Fig. 1), and since the array resolution was highest on this side of the rotor plane, the blades were only scanned during their downward movement (from 0° to 180°, with 0° the upper vertical blade position). In order to limit processing time, only the first two rotations after the start of each acoustic measurement were processed (one at a time). In the discussion of results (Section 3.2) it will be shown that, despite the use of only one rotation, the signal-to-noise ratio and repeatability (correspondence between the results for the first and second rotation) are very good. The noise from the blades was quantified using an integration method for moving sound sources [6]. An integration contour was defined which surrounds the noise from the blade but excludes the noise from the rotor hub.

2.4 Test Program

During the test campaign, that lasted from 8-15 December 2003, a total number of 110 acoustic measurements was done, so that the target of at least 30 valid measurements (taken from Ref. 2) could be easily met. Therefore, a selection was made of the measurements with the most constant conditions during the measurement time of 30 s. Using the following criteria, 35 measurements were selected for further processing:

1) Variation of wind speed within 15% (and within 1.5 m/s) of average;
2) Misalignment angle smaller than 12°, variation within 2° of average;
3) Variation in rotor RPM within 8% of average;
4) Variation in blade pitch angle within 3° of average;
5) Overloads in acoustic data (e.g. due to wind gusts) less than 1%.

The 'misalignment angle' is the angle between the turbine axis (depending on wind direction) and the line from turbine to array (Fig. 4). The distribution of the 35 selected measurements over the different wind speed intervals is given in the table below. It can be seen that all wind speed intervals are well represented. The rotor RPM typically varied between 22 and 26.

wind speed at 10 m	5.5-6.5 m/s	6.5-7.5 m/s	7.5-8.5 m/s	8.5-9.5 m/s	9.5-10.5 m/s
# measurements	6	6	12	5	6

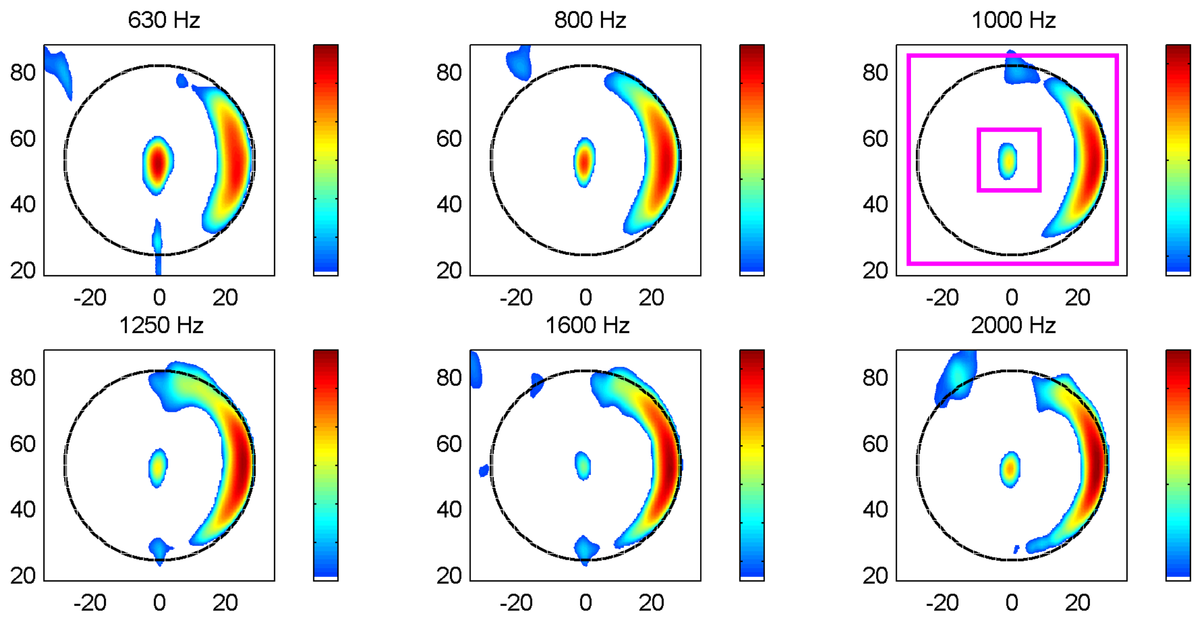

Fig. 3 Typical example of noise source locations in the rotor plane, as a function of frequency. The trajectory of the blade tips is indicated by the black circle. The range of the color scale is 12 dB. The pink lines (1 kHz) indicate the integration contours for the quantification of blade and hub noise

3 Results and Discussion

In this section the results of the acoustic measurements are presented and analysed. Section 3.1 describes the location and quantification of the noise sources in the rotor plane: the noise level from the rotor hub is compared to the blade noise levels, and trends in source locations are shown. Furthermore, the speed dependence of the blade noise levels is investigated. In Section 3.2 the noise sources on the individual rotating blades are analysed: the noise sources are localised and the levels from the clean, tripped, and untreated blade are compared.

3.1 Noise Sources in the Rotor Plane

Typical noise source distributions in the rotor plane are shown in Fig. 3. Note that these plots show the integrated effect of the three blades, averaged over the complete measurement time of 30 s (i.e. several rotations). A number of observations can be made from these plots. The most striking phenomenon is that practically all downward radiated blade noise (as measured by the array) is produced during the downward movement of the blades. Since the range of the color scale is 12 dB, this means that the (downward radiated) noise produced during the upward movement is at least 12 dB less than during the downward movement. This effect was observed for basically all measurements and all frequencies, and is very similar to results obtained earlier on a model scale wind turbine, where it was attributed to a combination of convective amplification and directivity of trailing edge noise [1]. It should be noted that for a different observer location the pattern may be different. A second important observation is that the noise from the blades clearly dominates the noise from the rotor hub. Furthermore, it can be seen that the blade noise is produced by the outer part of the blades, but not the very tip. The sources move outward for increasing frequency, which can be explained by the higher flow speeds and the smaller chord, resulting in a thinner boundary layer at the trailing edge (assuming that trailing edge noise is the responsible mechanism). Comparison of measurements with different rotor orientation shows that the location of the source region shifts upward or downward when the right- or left-hand side of the rotor plane is turned towards the array respectively (Fig. 4). This effect was also observed in reference 1, and can be attributed to the change in the component of the blade velocity in the direction of the array, which results in a change in convective amplification.

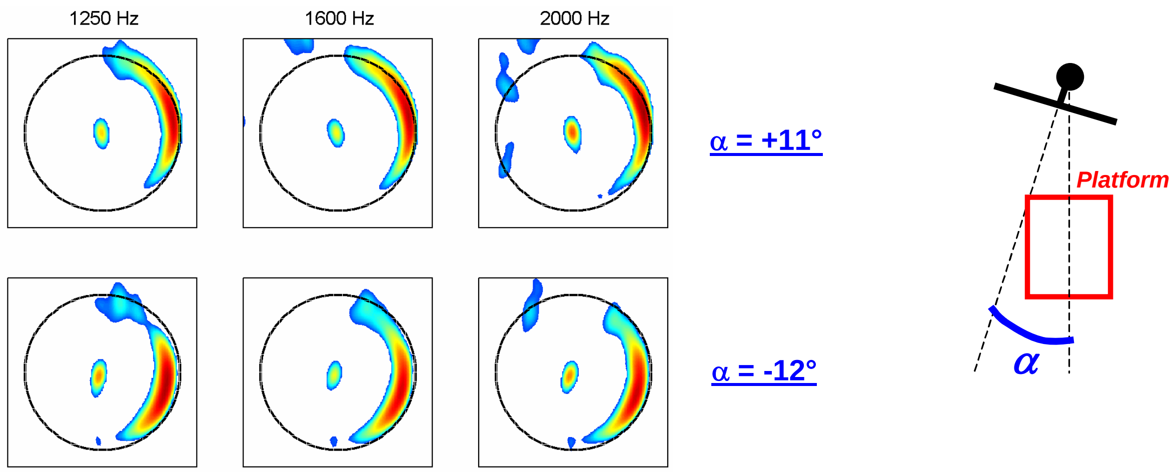

Fig. 4 Shift of blade noise location due to difference in misalignment angle α.

The noise from the blades and the rotor hub was quantified using the power integration method mentioned in Section 2. The integration contours are shown in Fig. 3: the small box was used for quantification of hub noise, while blade noise was defined as the difference between the large and small box. The spectra in Fig. 5 (averaged over all selected

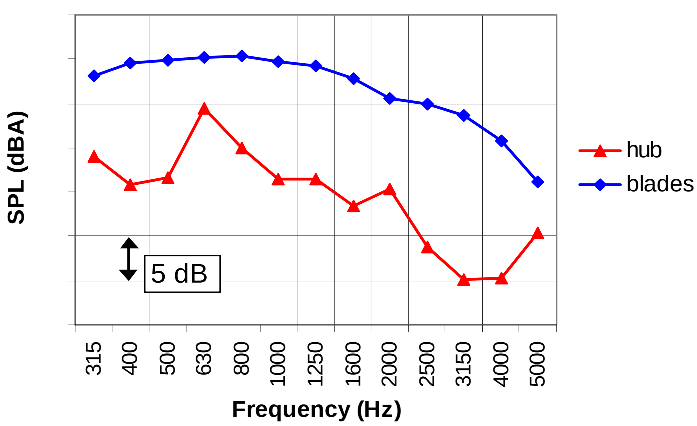

Fig. 5 Average spectra of hub noise and blade noise

measurements) confirm the observation in the source plots, that the blade noise is significantly higher than the noise from the hub. The hub noise shows a peak at 630 Hz, which is probably due to the gear box. The blade noise is broadband in nature, as would be expected for trailing edge noise. The highest A-weighted levels occur around 800 Hz. Interestingly, the blade noise spectrum seems to consist of two broad 'humps': a low-frequency hump centered at 800 Hz, and a high-frequency hump starting at 2 kHz. These two humps may be caused by trailing edge noise from the suction- and pressure-side boundary layers respectively. The difference between the overall sound pressure levels from hub and blades was found to increase with wind speed, from about 8 dB(A) at 6 m/s to about 11 dB(A) at 10 m/s. Apparently, blade noise increases faster than hub noise for increasing wind speed. In conclusion, blade noise is clearly dominant for this wind turbine.

The blade noise spectra for the individual measurements are shown in Fig. 6*a*. The speed dependence of the noise levels was investigated by plotting normalised levels as a function of Strouhal number $St=f \cdot L / U$, where f is frequency and L a typical length scale. For trailing edge noise, L is normally taken to be the boundary layer thickness at the trailing edge, but since this information was not measured a constant value of 1 m was chosen here. For this normalisation the undisturbed flow speed as perceived by the blade (U) was used, which is the vector sum of the wind speed and the rotational speed (the induced velocity is neglected). The rotational speed was calculated for a radius of 25 m, which is the location where we typically observed blade noise (Fig. 3). The noise levels were normalised as $SPL_{norm}=SPL-10 \cdot x \cdot log(U_{blade}/U_{ref})$, with SPL and SPL_{norm} the measured and normalised noise levels respectively. U_{ref} is a constant reference speed, for which here a value of 50 m/s was chosen. The variable x indicates the dependence of the blade noise on the flow speed: the acoustic energy is assumed to be proportional to the flow speed to the power of x ($p^2 \sim U^x$).

The normalised blade noise spectra are shown in Fig. 6*b*. The normalisation was done using a value of 5 for x, which seemed to give the best data collapse. This is indicative of trailing edge noise, since normally the value of x is around 5 for trailing edge noise, and around 6 for inflow turbulence noise [7, 8]. It can be seen that without normalisation the scatter in data is 5-10 dB, even when the quitest measurement is neglected. After normalisation the scatter is only 2-5 dB, including the quietest measurement. The remaining scatter in the normalised spectra is probably due to differences in turbine and weather parameters. It was investigated whether this scatter (after correcting for the speed effect) correlated with turbine orientation (i.e. misalignment angle) or blade pitch angle, but no clear relation was found.

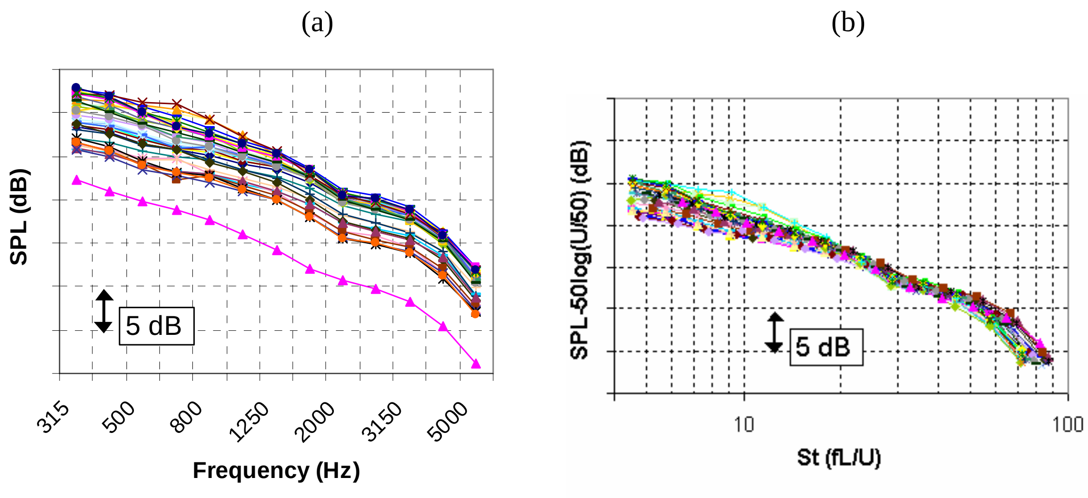

Fig. 6 Measured (a) and normalised (b) blade noise spectra for all selected measurements

3.2 Noise Sources on the Rotating Blades

Typical noise source distributions on the three rotating blades are shown in Fig. 7. Note that the signal-to-noise ratio is very good (i.e. 'clean' source plots), despite the fact that only half a rotation was used (see Section 2.3). These plots confirm the observations that were already made from the source plots of the rotor plane: most of the noise is produced by the outer blades and the sources move outward with increasing frequency. The blades are noisier than the hub and the relative importance of the hub is largest at 630 Hz (compare to Fig. 3). The resolution does not seem to be sufficient to determine whether the noise is radiated from the leading or trailing edge of the blade. However, the plots clearly indicate that the tripped blade is significantly noisier than the other two. This observation is a strong indication of trailing edge noise, since earlier studies [7] have indicated that tripping has no influence on inflow turbulence (leading edge) noise.

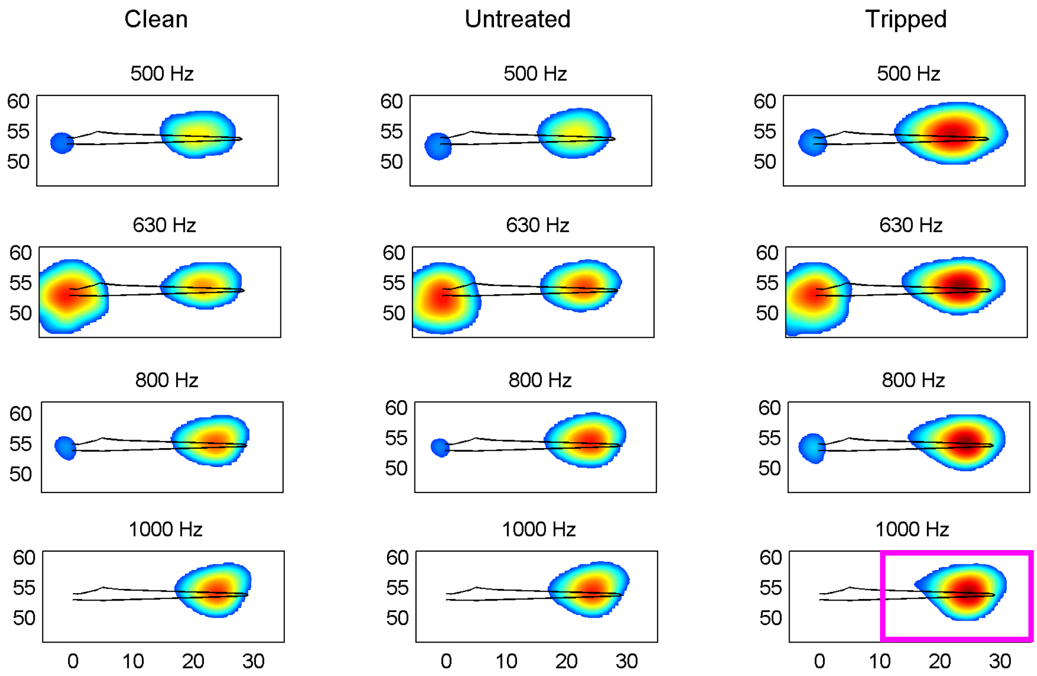

Fig. 7 Typical acoustic source plots showing the noise sources on the individual blades. The black line indicates the blade contour (leading edge on lower side). The range of the color scale is 12 dB and the color scale is the same for each row. The pink line (1 kHz) indicates the integration contour used for the quantification of the blade noise.

The noise from the individual blades was quantified using the method mentioned in Section 2.3. The integration contour used to quantify the blade noise is shown in Fig. 7. The resulting de-dopplerized spectra for the three blades, averaged over all selected measurements, are shown in Fig. 7. This figure clearly shows that the tripped blade is noisier than the other two for low frequencies, and that the tripped and untreated blades are slightly noisier than the clean blade at higher frequencies. The tripped spectrum peaks at 400 Hz, while the other two peak at 800 Hz. The lower peak frequency for the tripped blade may be due to an increased boundary layer thickness at the trailing edge. As explained in Section 2.3, the spectra in Fig. 8 were obtained using the acoustic data for the downward part (180°) of one rotation. To check the repeatability of the blade noise spectra, the spectra were also calculated using only the data for

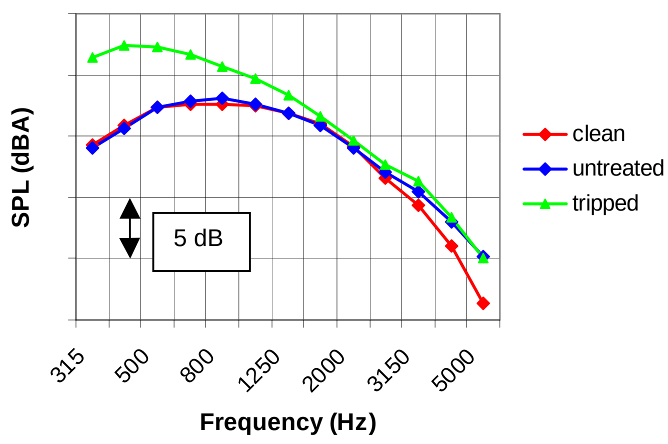

Fig. 8 Average noise spectra for the three blades.

the *second* rotation (not shown). It turns out that the differences in *average* blade noise levels between the first and second rotation are smaller than 0.3 dB for all frequencies, which indicates the good repeatability. For the individual measurements the differences were generally smaller than 1 dB.

Fig. 8 shows differences between the blades up to 7 dB at low frequencies, while at high frequencies differences up to 4 dB occur. The low-frequency differences are most important for the overall, A-weighted noise levels: the overall levels of the clean and untreated blades are practically identical, while on the average the tripped levels are 3.6 dB(A) higher. This level difference between the tripped and the other two blades was practically independent of wind speed.

Similar to Section 3.1, the speed dependence of the blade noise was further investigated by plotting normalised blade noise spectra as a function of Strouhal number. Again, the levels and frequencies were normalised using the flow speed at a radius of 25 m. As an example, the measured and normalised spectra for the tripped blade are shown in Fig. 9. These plots confirm that a good data collapse is obtained for x=5, which is indicative of trailing edge noise (compare to Fig. 6). Similar to the results in Section 3.1, the remaining scatter in the normalised spectra is probably due to differences in turbine and weather parameters.

The acoustic results can also provide information about the flow state on the untreated blade, which is representative for a turbine blade during normal operation. The similarity between the noise levels of the clean and untreated blade suggests that the untreated blade was aerodynamically clean (i.e. no boundary layer transition close to the leading edge). However, an alternative explanation could be that both the 'clean' and 'untreated' blades were in fact dirty (i.e. transition close to the leading edge), because there was about one week between the cleaning of the blade and the acoustic measurements. The higher levels for the tripped blade could then be explained by the relatively large trip thickness (0.4 mm), which may have caused overtripping. To resolve between these two possibilities, acoustic wind tunnel tests were performed in which the trailing edge noise levels of the GAMESA airfoil were measured for several types of tripping [9]. These measurements showed that the noise levels for the GAMESA airfoil with a 0.4 mm zigzag tape (as in the field measurements) were practically identical to those for a 2D turbulator strip with a thickness of 0.18 mm. This means that the zigzag tape did not cause overtripping. Moreover, the spectra for the tripped airfoil showed a low-frequency noise increase with respect to the clean airfoil, similar to the low-frequency increase observed in Fig. 8. Thus, it seems that the untreated blade was in fact aerodynamically clean during the field tests.

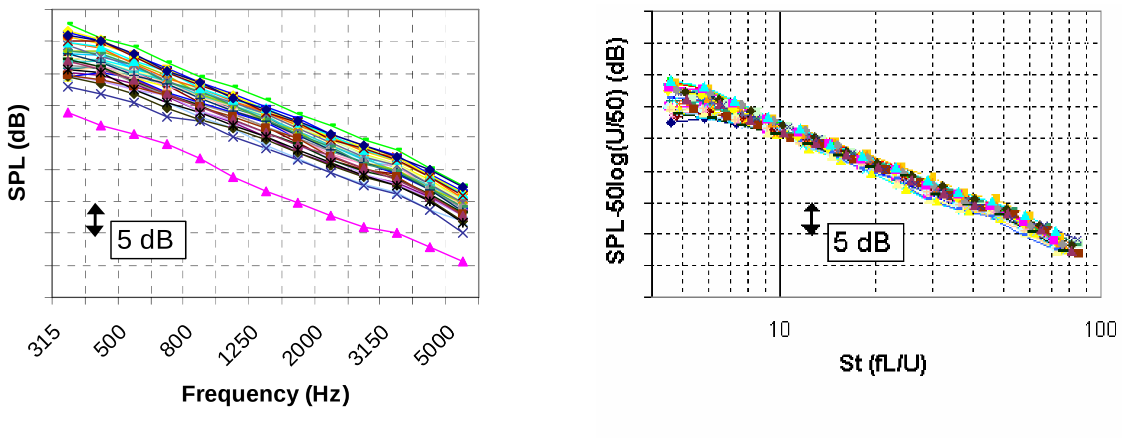

Fig. 9 Measured (left) and normalised (right) noise spectra for the tripped blade

The above argumentation applies to the low frequencies, which are considered to be produced by the (thick) suction side boundary layer. A possible explanation for the small difference in high-frequency noise between the clean and untreated blade, could be that only the pressure side of the untreated blade was contaminated, causing increased levels at high frequencies. However, insect impact calculations [10] indicate that if contamination occurs, it will occur on both suction and pressure side. Thus, no explanation is available yet for this high-frequency effect.

4 Conclusion

Acoustic array measurements were performed on a GAMESA G58 wind turbine, to characterize the noise sources and to verify whether aerodynamic noise from the blades is dominant. In order to assess the effect of blade roughness, one blade was cleaned, one blade was tripped, and one blade was left untreated. Two array processing methods were used to localise and quantify the noise sources in the rotor plane and on the individual blades. The main conclusions can be summarised as follows:

- Aerodynamic noise from the blades is the dominant noise source for this turbine;
- Practically all noise (emitted to the ground) is produced during the downward movement of the blades;
- The blade noise is produced by the outer part of the blades, but not by the very tip;
- Blade noise levels scale with the 5^{th} power of the local flow speed;
- The tripped blade is significantly noisier than the clean and untreated blade;
- The acoustic results suggest that the untreated blade was aerodynamically clean.

In principle, there are two mechanisms which may be responsible for the aerodynamic noise from the blades [11]. The first is inflow-turbulence noise (IT noise), which is radiated from the leading edge of the blade, and which is caused by upstream atmospheric turbulence. The second mechanism, trailing edge noise (TE noise), is caused by an interaction of boundary layer turbulence with the blade trailing edge. The present test results strongly suggest that TE noise is the responsible mechanism for the present turbine. The most important evidence for TE noise are the increased levels for the tripped blade, since it has been shown before that tripping has no influence on IT noise levels [7]. Furthermore, the 5th power speed dependence and the noise source distribution in the rotor plane are indicative of TE noise.

The next step in the project consists of acoustic field measurements on the same GAMESA turbine with a newly designed blade (planned for September 2005). This blade is optimized for low TE noise emissions, while keeping the aerodynamic performance the same. The turbine rotor will consist of one optimized blade and two baseline blades, so that the noise levels can be compared for identical inflow conditions. Besides the new blade design, reduction concepts such as trailing edge serrations [1] may be tested as well.

5 Acknowledgments

The authors would like to thank the colleagues from the University of Stuttgart and from the Netherlands Energy Research Foundation (ECN) for their valuable contributions to the definition of the tests and the interpretation of the results. Financial support for this research was given in part by the European Commission's Fifth Framework Programme, project reference: SIROCCO, Silent Rotors by Acoustic Optimisation (ENK5-CT-2002-00702). Financial support was also given by the Netherlands Organisation for Energy and the Environment (NOVEM).

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